Evaluating display color capability

Citation for the original published paper (version of record):
Smith, E., Heckaman, R., Lang, K. et al (2020). Evaluating display color capability. Information Display, 36(5): 9-15. http://dx.doi.org/10.1002/msid.1145

Evaluating Display Color Capability

Although the CIE recommends using the 3D CIELAB color space to assess displays, a 3D CIELAB gamut plot can be difficult to calculate, render, and interpret. Here, a team of experts demonstrates why the gamut rings plot may be a better alternative.

by **Euan Smith, Rodney L. Heckaman, Karl Lang, John Penczek, and Johan Bergquist**

ALTHOUGH HUMANS' PERCEPTION OF COLOR IS THREE-dimensional (3D), we often characterize a display's color capability using the two-dimensional International Commission on Illumination (CIE) 1931 or CIE1976 chromaticity diagram. Initially, there were good reasons for this, and in the age of the cathode-ray tube (CRT) display, it was a reasonable approximation. However, for modern displays, this is no longer the case. In this article, we show that the gamut rings plot,[1] proposed by Kenichiro Masaoka of Japan's national broadcaster NHK and colleagues, is an alternative that accurately expresses a modern display's color capability at a glance. We also describe how to generate the plot using software tools that we made open source and publicly available.[2] (See our "Quickstart Guide" on page 15 for more.)

Color perception derives from responses of the retina's three types of cone cell photoreceptors. No matter the color model used to evaluate it, our color perception has three dimensions. In colorimetry, we interpret our visual response to a color stimulus using the CIE color-matching functions, converting any spectra of visible light into the well-known CIE XYZ tristimulus response. This three-value system is the basis for all color metrology.

To encode a color, simplified color spaces such as red, green, and blue (RGB) or a polar coordinate equivalent such as hue, saturation, and lightness (HSL) are used. Three dimensions are required to encode a color, as well as to quantify our response to it.

The CIE is the body that, for more than 100 years, has developed the preeminent international standards regarding color's measurement and modeling. Since the CRT's early days, display engineers have used the two-dimensional CIE1931 x,y chromaticity diagram to describe a display's primary color emitters—a direct derivation from XYZ that removes the quality of luminance (dark to light) from the equation. It maps only the hue and saturation components.

This shorthand for describing the CRT phosphor was useful. The display output, from light to dark, was a simple function of the power applied to the phosphor from the electron gun. All that was needed to understand a CRT display's color capability was the position of each phosphor on the x,y diagram and the position of the white point. A phosphor of a particular chromaticity linearly mixes along a vector with another, and the complete triangle describes the range of chromaticity possible. Adding the actual luminance of white completed the full description of a CRT's color capability, as the RGB intensities required to produce a particular white are uniquely defined by additivity.

Display technology has progressed significantly since the CRT. Modern display systems no longer have signal input channels that directly control the output color emitters.[3] Digital signal processing mixes the input signals, and the direct correspondence that was required to properly interpret the chromaticity diagram is lost. Some modern display systems have more colorants than just the fundamental RGB—for example, adding white or yellow subpixels. For such systems, the mixing required to produce the white is no longer unique and can't be predicted. In modern displays, the chromaticity diagram's utility completely breaks down. In some instances, as we will show, it can be actively misleading.

Color science also has made great strides since 1931. The XYZ tristimulus response quantifies only physically measurable

QUICK TAKE

The chromaticity diagram shows a set of primaries' color reproduction potential, but the gamut rings plot makes plain the display's real color performance.

quantities. Systems such as CIE 1976 L*a*b* (CIELAB)—the color space recommended by CIE to assess displays' color capability—instead model color perception in a way that is uniform and homogenous and adapts as our vision adapts. We do not perceive color as absolute; it is always relative to the context in which it appears. A patch with a given XYZ response might appear yellow against one background and brown against a brighter background. This subtlety cannot be and is not expressed in a CIE1931 chromaticity diagram.

However, 3D color spaces, such as CIELAB, are hard to communicate and interpret. The chromaticity diagram is still in use by habit, and because of other options' complexity versus a 2D plot's convenience. As an alternative, the gamut rings plot can express much of what is important in a full 3D color gamut plot, but with the convenience and clarity of a 2D chart.

Representing Color Capability

Humans' perception of color is complex. The response of a rod or cone cell to light is simple enough to assess, but this signal is then processed both within the retina and the visual cortex. What we perceive, then, is far from a simple transform of that initial optical stimulus. We know that our visual perception is not linear—an object that reflects twice as much illumination as a neighboring object only appears about 20 percent brighter. We also know that our vision adapts to the environment it observes and that our perception of color (HSL) is always relative to the surrounding light. Finally, our perception of color is completely independent of the physical process producing the light. It does not matter if the light was emitted by or reflected off an object. The only thing that matters is the light we observe.

For a quantitative measurement of a display's color capability, we need a color space that models our color perception's complexity. It needs to quantify our perception of HSL (or equivalents), and be adaptive in the same way our vision is adaptive. Finally, and critically, for the measurement of an enclosed volume in such a color space to be meaningful, it must also be uniform and homogeneous. A step of a given magnitude in any direction and from any point must equate to an equivalent difference in perceived color.

The initial application area for CIELAB was in the assessment of printed color. However, by design, it was developed to be device-independent and broadly applicable. CIELAB is fully adapted (to the reference white point in a scene), and reproduces the nonlinearity of human vision. Importantly, a step of 1 unit in any direction (in L*, a*, or b*) from any point in CIELAB space represents, to a good approximation, the same degree of perceived color difference.

The L* of CIELAB indicates lightness and varies from 0 (black) to 100 (the reference white); a* approximately indicates green-red color difference (more negative a* is greener), and b* indicates blue-yellow color difference. A common variant, instead of using the Cartesian coordinates (a*, b*), is to use polar coordinates h (hue) and C (chroma). However, the resultant plots are the same. **Fig. 1** shows the standard RGB (sRGB) reference color gamut plotted in CIELAB space. The size of the volume enclosed by the CIELAB color gamut surface indicates the display's color capability. (We describe how to measure this surface and volume later.)

The 3D shape of the display color gamut encodes a great deal of information about the display's capabilities. However, we can only ever assess one 2D projection of the 3D shape at a time. It is difficult enough to examine the gamut volume from different viewpoints using a computer; it is even more challenging to publish a plot in a magazine or journal where only one or two static views are possible.

The difficulty of interpreting a 3D surface, the challenges in communicating the results, and the inertia from the chromaticity diagram's historical use have hindered CIELAB's adoption as the standard way to show a display's color performance. However, as we will demonstrate, using the chromaticity diagram to describe color capability is no longer an acceptable approximation.

Testing Chromaticity as Displays Evolve

When the CIE chromaticity diagram was first used to assess the color performance of displays, there was only one display technology available, the CRT, with little fundamental variation in how a color signal was converted into a picture. CRT displays are emissive and additive with white light emission, for example, equaling the sum of the RGB emissions. To test how well chromaticity correlates with the real color capability assessed using CIELAB color gamut volume, 1,000 synthetic display gamuts were simulated by taking a random set of RGB emission colors for each display gamut and balancing their luminance so that the white point is the standard D65 illuminant. The CIE1931 chromaticity area and CIELAB color gamut volume were then calculated and plotted. As **Fig. 2** (left) illustrates, in this case, they correlate well; the sRGB, Digital Cinema Initiatives (DCI)-P3, and BT.2020 gamuts also are included for reference. So, initially at

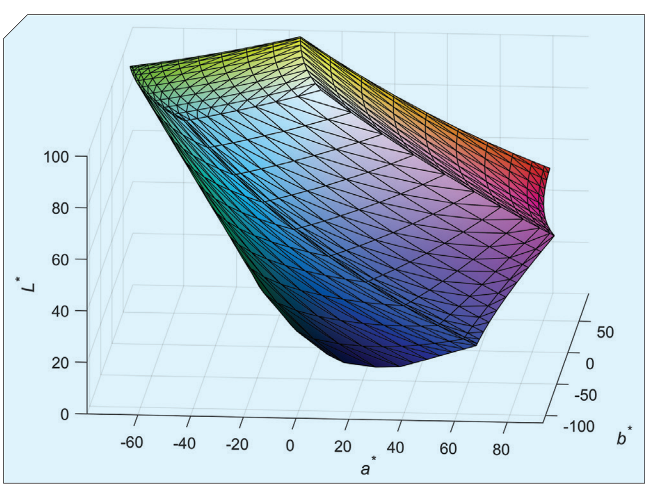


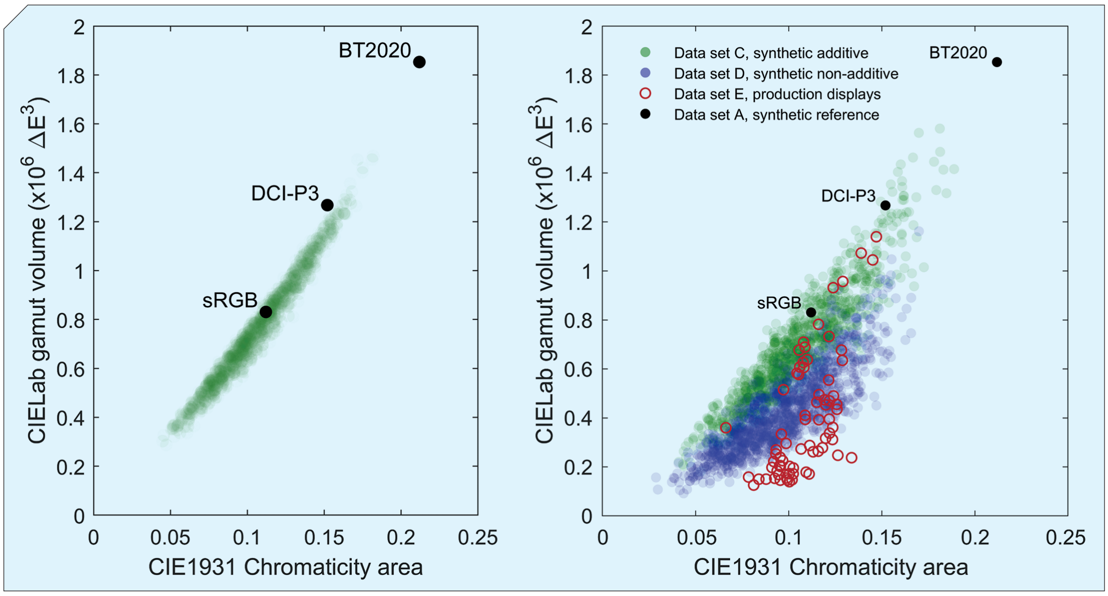
Fig. 1.

International Commission on Illumination 1976 L*a*b* (CIELAB) plot of the standard red, green, and blue (sRGB) color gamut.

All figures courtesy of the authors.

Fig. 2.

Gamut volume versus chromaticity area for synthetic random cathode ray tube (CRT)-like displays (left) and synthetic and production modern displays (right).



least, it seems that for a CRT or other additive displays, the CIE1931 chromaticity is a reasonable approximation.

Modern displays are more complicated. There are many more levers available to the display engineer to tailor a display for a particular application, including more complex display drive schemes, signal mappings and transforms, additional subpixels, and adaptive display performance. To simulate some aspects of modern display design, two further sets of synthetic display gamuts were calculated and plotted in **Fig. 2** (right). For the synthetic additive set, the white point could vary. For the synthetic non-additive set, between 25 percent and 75 percent white boost (where a white subpixel is added to help boost the white luminance) was added, and the contrast ratio could vary. It is clear that the reasonable correlation between chromaticity area and gamut volume no longer holds. This becomes even more evident when adding measurements from a large number of production displays (also shown in the figure). In the worst case, the color gamut volume of two displays with the same chromaticity area can vary by as much as a factor of three or four.

The area derived from RGB chromaticities is a good indicator of the display's potential color capability. However, engineering trade-offs can result in a final product with a lower color capability. This may be done, for example, to improve peak luminance where that is more important, or reduce power consumption. For modern displays, where many such design decisions can impact color performance, the only way to properly assess the color capability is in spaces with the adaption and perceptual uniformity of CIELAB.

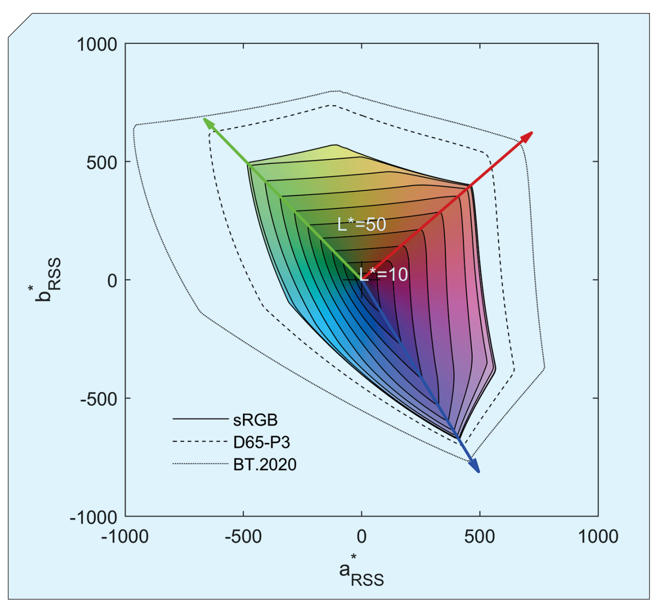
Gamut Rings Offer Accuracy

Fig. 3 is an example of a gamut rings plot that shows the sRGB gamut in comparison to the DCI-P3 and BT.2020 gamuts. In essence, the gamut rings plot shows a CIELAB gamut that has been flattened out, transforming the CIELAB gamut volume into an area. Imagine a CIELAB gamut plot divided into slices 10 units of L* thick, with each slice flattened into an area proportional to its volume. Starting with the slice below, L*=10, each subsequent slice is stretched to surround the previous slice, building up the set of increasingly larger rings shown in the figure. Each ring encloses an area equal to the total gamut volume up to the L* value of that ring, with the final (L*=100) ring enclosing an area exactly equal to the total CIELAB gamut volume. Reference gamuts are typically shown with just the final ring as a dashed line.

An important feature of this plot is that the hue directions are maintained. If the red primary of a display is at a hue angle of

Fig. 3.

Gamut rings plot of reference color gamuts.



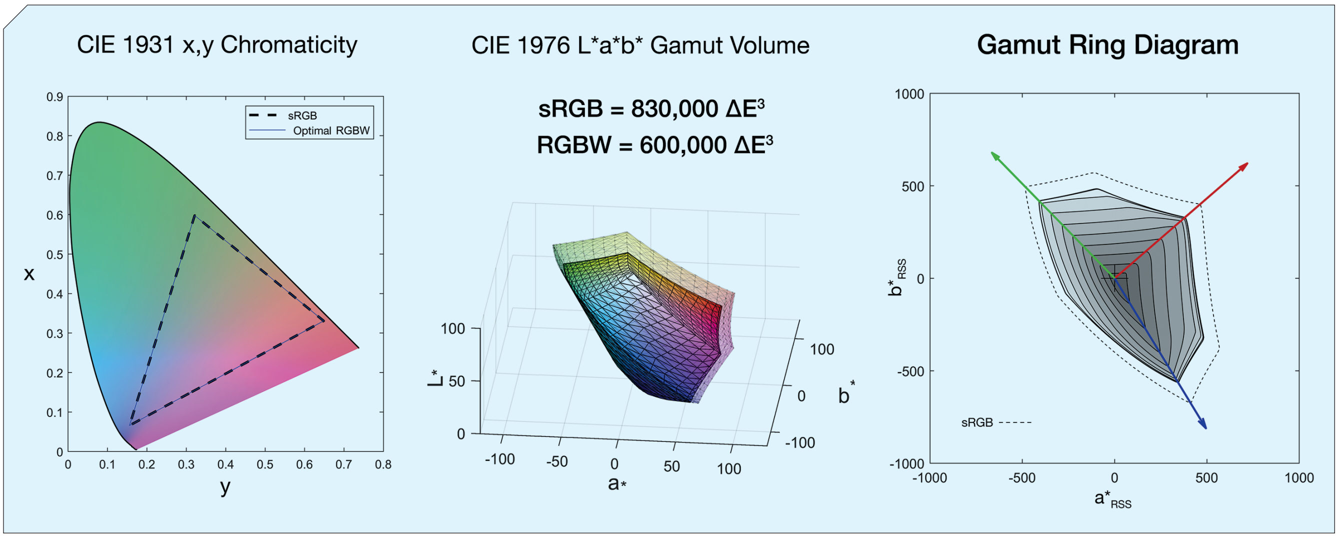


Fig. 4.

Chromaticity diagram (left), CIELAB gamut volume (middle), and gamut rings (right) plots comparing an ideal sRGB display to a synthetic RGB white (sRGBW) display.

40 degrees in CIELAB space, then a red peak will show in the gamut rings plot at the same angle. The outer rings of each of the reference color gamuts show six such peaks: one each for red, yellow, green, cyan, blue, and magenta. At a given hue angle, the further out the outer line is from the center, the wider the range of colors a display is able to reproduce of that given hue. If a ring of a given L* at a given hue is close to the previous ring, then that display has little capability to reproduce colors of that hue at that lightness. As **Fig. 3** shows, it is only in the yellow area that the outer sRGB ring extends out from the previous ring, precisely because yellow is the color which can be rendered with the highest luminance (other than white). Vectors indicating the hue angles of full-signal RGB have been added to the plot to aid interpretation.

The gamut rings plot is able to show, in a single 2D figure, the display color capability resolved by hue and lightness. It clearly shows the overall color gamut volume, particularly when plotted with a reference gamut. Although there is still more detailed information to be obtained from the full 3D CIELAB plot, the gamut rings plot shows simply and unambiguously the key aspects of a modern display's color capability.

Measuring Color Capability

To assess a display's color capability, the CIELAB surface of the color gamut must be measured. A full discussion of the requirements can be found in many sources, including CIE 168[4] or the Information Display Measurements Standard (IDMS).[5] In essence, the display's XYZ tristimulus response must be measured for a range of RGB input signal levels to sample points on the CIELAB gamut surface. We can take advantage of the fact that points on the surface of the RGB color space cube map to surface points on the CIELAB boundary. It was empirically found that good accuracy is obtained by subdividing each face of the RGB cube into a grid of 11 x 11 points—602 measurement points total. Then the code we provide in the "Quickstart Guide" on page 15 can be used to plot and analyze the data if presented either as a standard American National Standards Institute, American Standard Code for Information Interchange, and Committee for Graphic Arts Technology Standards (ANSI/CGATS.17-2009) file,[6] or as arrays of RGB and XYZ data in Matlab or Octave. The next revision of the IDMS should also contain code sufficient for processing and analyzing gamut surface data.

Assessing Display Modeling and Measurement Results

We present three examples of gamuts that clearly demonstrate the power of the gamut rings plot: a synthetic white-boosted display and experimental results from commercial LCD and projection displays.

USING A SYNTHETIC WHITE-BOOSTED DISPLAY

The white boosted display was modeled as an sRGB display with an additional white subpixel that has a luminance equivalent to 50 percent of the R+G+B luminance, often referred to as a 50 percent white boost. This typically is used only to boost lighter colors' luminance. **Fig. 4** shows the results. For comparison, **Fig. 4** also includes the chromaticity diagram, which of course shows no difference between the displays. The CIELAB volume plot shows there is an overall volume difference, but it is difficult to clearly perceive that difference's magnitude. The gamut rings plot shows the correct scaling (the synthetic gamut volume is 72 percent of the reference)—and if the rings are examined carefully, we can see that the L*=90 and L*=100 rings are virtually on top of each other and indistinguishable in the figure. Near the peak of display luminance, there is virtually no capability to display color.

CHECKING A COMMERCIAL LCD

A production RGB white (RGBW) LCD display was measured in

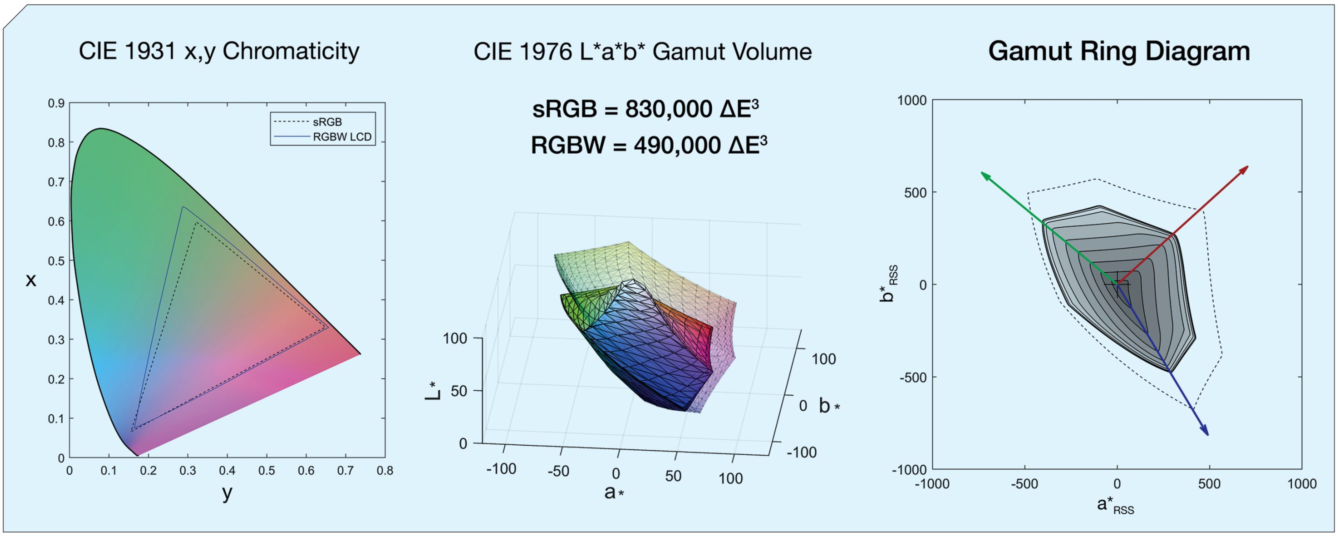


Fig. 5.

Chromaticity diagram (left), CIELAB gamut volume (middle), and gamut rings (right) plots comparing an ideal sRGB display to a production RGBW LCD.

darkroom conditions according to best practices, as outlined in IDMS.[5] **Fig. 5** shows the results with the same set of plots for chromaticity, CIELAB, and gamut rings as before, with sRGB as the reference. The chromaticity diagram shows a set of primaries enclosing an area 113 percent of sRGB. However, the real color capability—plotted in CIELAB space and quantified in terms of the gamut volume—was only 59 percent of sRGB. The reason for this discrepancy can be seen in the CIELAB plot, with the signature sharp spike toward white that is indicative of a considerable white boost. The reduced color capability, compared to sRGB, is shown clearly in the reduced area of the gamut rings plot. The rings from L*=70 outward lie virtually on top of one another, showing very little color capability at high luminance.

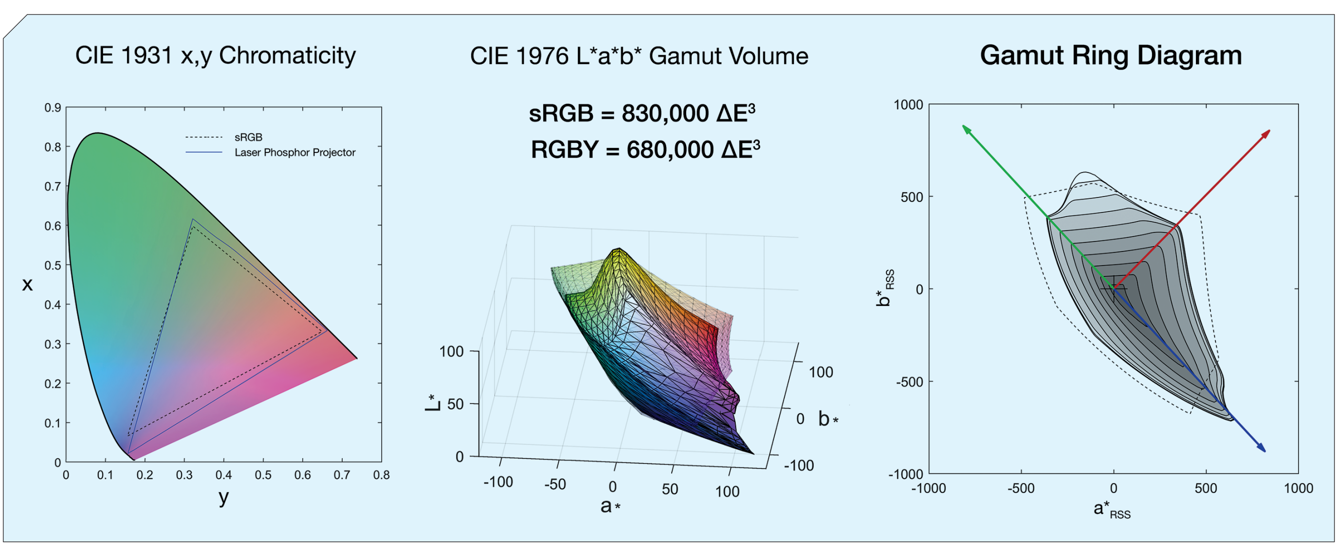
INVESTIGATING A RGB YELLOW (RGBY) LASER PHOSPHOR DISPLAY

The final example is a commercial projection system that uses a blue laser to excite a yellow phosphor, with the resulting light split into four colorants—red, green, blue, and yellow. **Fig. 6** shows the results. As with the RGBW LCD example, the chromaticity area is 115 percent of sRGB. However, the CIELAB gamut plot shows a very complex irregular gamut hull that could not be deduced from the chromaticity diagram. This 3D plot is a good example of a gamut shape that is hard to assess from a single 2D perspective view.

The gamut volume was calculated to be 82 percent of sRGB, again showing that the chromaticity area can give a misleading impression of the display's color capability. The gamut rings diagram shows this total volume reduction and demonstrates the

Fig. 6.

Chromaticity diagram (left), CIELAB gamut volume (middle), and gamut rings (right) plots comparing an ideal sRGB display to a RGB yellow (RGBY) laser phosphor projector.



unique features of this display's color capability. The display has a remarkably strong yellow and deep blue capability. The rings also reveal the weak green and red of this system. By examining the red and green vectors, we see that brighter rings are tightly spaced, indicating a lack of luminance in those hue regions. We observe a slight hue error in red and a large hue error in blue when comparing the hue vectors with the sharp points in the rings of the reference sRGB gamut.

As we discussed here, color is a 3D quality and is always relative to a local white point. For many years, the 2D CIE1931 chromaticity diagram has been used to express a display's color capability. But while this was reasonable in the CRT era, it is no longer ideal. A modern display's color capability is not proportional to the area enclosed by the RGB primaries on a chromaticity diagram.

The CIE recommends the 3D CIELAB color space to assess the visual appearance of any media, including displays. The CIELAB color space adapts fully to a reference white. It models the nonlinearities of the human vision system and is uniform and homogenous. In short, it meets all the requirements required to evaluate color capability. Unfortunately, a 3D CIELAB gamut plot is harder to calculate, render, interpret, and communicate than a 2D plot. This has prolonged the use of the CIE1931 chromaticity diagram, even though it often yields a misleading view of the display's capability.

As a solution, the gamut rings plot clearly and accurately expresses a display's color capability in a 2D plot and is a simpler way to communicate the CIELAB information. We made the algorithms and calculations required to produce the plot and released them to the public in an open source code base, with no restrictions on where and how they are used.

References

[1] Masaoka K, Jiang F, Fairchild MD, and Heckaman RL. 2D representation of dipslay color gamut. SID Digest. 2018;49:1048-1051.

[2] Smith, E. CIELab gamut tools. GitHub [Internet]. 2020. Available from: https://github.com/CIELab-gamut-tools/gamut-volume-m.

[3] International Electrotechnical Commission. Measurements of optical properties—multi-colour test patterns. IEC TR 62977-2-3. Geneva Switzerland: International Electrotechnical Commission. 2017.

[4] International Commission on Illumination. Criteria for the evalutaion of extended-gamut colour encoding. CIE 168. Vienna, Austria: International Commission on Illumination. 2005.

[5] International Committee for Display Metrology. Information display measurements standard [Internet]. Hoboken, NJ: Society for Information Display. 2012. Available from: https://www.icdm-sid.org.

[6] American National Standards Institute. Graphic technology—exchange format for colour and process control data using XML or ASCII text. ANSI/CGATS.17-2009. New York, NY: American National Standards Institute. 2009.

QUICKSTART GUIDE

Follow these directions to generate a gamut ring plot using the software tools that we have made open source and publicly available.

First, follow the "Installing Prerequisites" instructions in the project repository[2] at https://github.com/CIELab-gamut-tools/gamut-volume-m.

Open Matlab or Octave. We will start by recreating **Fig. 1**, for which we will need to generate a synthetic sRGB gamut using the *SyntheticGamut* function:

```
sRGB = SyntheticGamut('srgb');
```

Then plot it:

```
PlotVolume(sRGB);
```

With this, you can now freely rotate and view the CIELAB gamut plot from different directions.

Most of the functions in the library either generate a gamut object (*SyntheticGamut* and *CIELabGamut*) or use it (*PlotVolume* and *PlotRings* for visualizations or *getVolume* to return the gamut volume). The one exception is *IntersectGamuts*, which takes two gamuts and returns their intersection. Please note, however, that the gamut generated cannot be used with *PlotVolume*.

Next, we are going to recreate some of **Fig. 5** using *CIELabGamut* to load the measured LCD data provided in a sample file. To plot it along with the sRGB data, we use a second parameter of the *PlotVolume* function that specifies opacity. Between the two plots, *hold on* is a standard function that prevents plots being overwritten:

```
lcd = CIELabGamut('samples/lcd.txt');
PlotVolume(sRGB, 0.3);
hold on
PlotVolume(lcd);
```

Finally, to produce an equivalent gamut rings plot in a new figure, we use the *PlotRings* function. To recreate exactly the rings plot in **Fig. 5**, we also include options to make the rings monochrome and to display the RGB primary vectors.

```
figure;
PlotRings(lcd, sRGB, 'BandChroma', 0, 'Primaries',
'rgb', 'LLabelIndices', []);
```

For any of the included functions—*SyntheticGamut*, *CIELabGamut*, *PlotVolume*, *PlotRIngs*, *GetVolume*, or *IntersectGamuts*—either enter "*doc <command-name>*" to get mode details on parameters and options, or refer to the documentation in the project repository.

Euan Smith, Ph.D., is the inventor of 40 patent families and more than 160 patents covering OLED devices and display drivers, organic thin-film transistors, optics, image processing, and touch interaction. Smith is a technical expert for the British Standards Institution and a member of the International Electrotechnical Commission (IEC) committee TC110. A contributing author to the *Handbook of Optoelectronics*, he received his Ph.D. in nonlinear optics from Heriot-Watt University in Edinburgh, Scotland. He can be reached at *esmith@lifesize.com*.

Rodney L. Heckaman, Ph.D., is a scientific research and development consultant in the field of color science with applications to display media technology, color perception, and image science. He spent 33 years as a research and development engineer at the Eastman Kodak Company. Heckaman received his Ph.D. from the Rochester Institute of Technology in Rochester, New York.

Karl Lang is a color scientist/engineer and the principle of Lumita, Inc. With 30 years of experience in the digital imaging industry, he has designed, developed, and brought to market numerous products and provided consultation services to companies such as Apple and Sony. Lang is a member of several display metrology standards organizations. He serves on IEC WG13 and WG10 and is the chair of the International Committee for Display Metrology (ICDM) Color Volume and Accuracy Workgroup.

John Penczek, Ph.D., is a senior research associate at the University of Colorado Boulder and a guest researcher at the National Institute of Standards and Technology in Boulder, Colorado. His areas of interest include display metrology development for 3D, transparent, and augmented/virtual reality displays. He's also a long-serving US expert on display metrology in IEC and International Organization for Standardization international standards.

Johan Bergquist, Ph.D., is an independent consultant whose current research interests include display metrology, image quality, and color capability. He was formerly a senior adviser to the Japan-based Semiconductor Energy Laboratory (SEL) and, among other things, has been a senior research engineer at the Visual Communications Laboratory of Nokia Research Center and a principal scientist at Nokia Bell Labs in Tokyo. Bergquist received his M.S. and Ph.D. degrees in physics from the Chalmers University of Technology in Göteborg, Sweden.